International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249–6890; ISSN (E): 2249–8001
Vol. 11, Issue 6, Dec 2021, 275–282

THEORETICAL AND EMPIRICAL DEVELOPMENTS FOR AFFORDABLE HIGH PERFORMING PHOTOVOLTAIC SYSTEMS AND REVIEW OF GOVERNMENT MUNICIPAL BEHAVIOUR: CASE STUDY CITY OF UMHLATHUZE

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ABSTRACT

Photovoltaic (PV) systems are one of the leading technologies in the renewable energy sector, generating much needed sustainable energy at relatively high efficiencies. Theoretical evaluations of PV systems are considered in this paper together with empirical research that ensures that high efficiencies are maintained whilemaking the system affordable for municipal buy-in. The issue is the provision of affordable electricity to citizenry compared to conventionally generated electricity from coal-fired power stations, and examination of the efficiency of electricity production from renewable PV technology compared to conventional technology. Thispaper highlights the contribution of advances made by researchers through empirical methods to attain high efficiencies through cost effective means.

KEYWORDS: Photovoltaic Systems, Cost Effective, Affordable, High Performance, Empirical Methods & Theoretical Evaluations

Received: Sep 11, 2021; **Accepted**: Oct 01, 2021; **Published**: Nov 06, 2021; **Paper Id**.: IJMPERDDEC202117

Original Article

1. INTRODUCTION

High energy demand as a result of the world's increasing industrialisation and the need for exponential economic growth has motivated the use of alternative energy sources to provide a reliable and sustainable energy supply. One of the alternative energy sources that can be used to generate electricity is solar energy. Using the photoelectric effect, photovoltaic systems can supply direct current (DC) power to the load (energy-using devices). Franklin (2018) states that solar photovoltaic (PV) energy systems must be designed and configured against the load type and match the energy need (load).Various researchers and authors state thatthe amperage produced by a PV module or array is determined by the number of cells contained and the size or area of each cell. Franklin (2018) confirms the above and states that the larger the cell, the higher the amperage that gets produced.

The government in South Africa is one of the biggest buyers of goods and services and in order to attain government buy-in at the municipal level, efficiency of a module (or array) together with cost consideration is of utmost importance in order to attain government buy-in. In order to achieve high efficiency at minimal cost, apart from considering the size of the cells, the make-up of the cells is important. Thus, this paper seeks to examine possible improvements or alternatives readily available in the South African environment, and surveys research by other researchers and manufacturers on the development of efficient low cost modules and PV system components.

2. METHODOLOGY

2.1. Theoretical Improvement of Photovoltaic Modules and Empirical Developments that make Photovoltaic Systems Affordable for Municipal use

Dobrzanski et al. (2013) define solar cells as devices that convert light energy from the sun's rays directly into electricity by photovoltaic effect. According to various authors and researchers, early modules weremono-crystalline based. Over the years, two PV module types emerged; modified mono-crystalline modules developed from stringent treatment processes aimed at improving performance and efficiencies, and the less expensive poly-crystalline based modules. Franklin (2018) attests to the above and states that one of the factors contributing to cost increasesfor PV system moduleswas the way in which the cells were manufactured.Earlier modules housedround mono-crystallinecells that resulted inempty spaces when arranged in a module, thus hampering the module efficiencies. But advances in the PV system cell development has led to the manufacture of square or rectangular cells that lessen material wastage while retaining or improving efficiencies.

The National Renewable Energy Laboratory together with the United States Environmental Protection Agency (2013) reported that solar PV panels are environmentally friendly, and that two common PV technologies exist; crystalline silicon (either monocrystalline or polycrystalline) and thin film (made of amorphous silicon). The report highlights that thin film solar PV modules have lower efficiencies of 6.5 % to 8% when compared to efficiencies of crystalline cells.

An advance in PV module systems occurred in the selection of materialswith PV cells being silicon-crystalline based.The introduction of silicon crystalline PV cells improved efficienciesupto 20% when compared to standard cells that have 12 % to 18% efficiencies. Metallurgical research improved the crystalline formation required for high-efficiency (monocrystalline) PV cells to be achieved. Saga (2010) states that lengthy processes are involved in producing the complex crystalline structure of high efficiency PV cells, therefore they are costly to manufacture and hence costly in the market.

Salah (2019) states that due to the high costs associated with solar PV cell manufacture, alternative manufacturing techniques that significantly reduce high temperature processing such as vapour deposition and electroplating were researched andemployed. Saga (2010) describes monocrystalline silicon as a single-crystal product of the Czochralski process and the polycrystalline silicon as square silicon substrates cut from polycrystalline ingots in quartz crucibles that have been carefully cooled and solidified. Sangwal (2013) describes the Czochralski process as melting silicon by induction or resistance heating under controlled conditions for the purpose of growing silicon ingots that are eventually cut into thin silicon slices known as wafers. Dobrzanski et al. (2013) point out that polycrystalline solar cells are less efficient than monocrystalline cells but cheaper to producedue to less treatment process activities needed and less energy required. The authors state that monocrystalline wafers are expensive because of the methods used to cut the cylindrical ingots to wafers (very thin silicon plate). Saga (2010) states that 50% of the cost of a PV system results from module costs and quantifies the breakdown of the entire fabrication costs of a solar PV cell module as comprising 50% silicon substrate, 20% cell processing and 30% of module processing.

Certain materials can act as semiconductors (become electrically conductive when supplied with light energy) and so be used in producing solar cells,namely; crystalline silicon, cadmium telluride, copper indium diselenide, gallium arsenide, indium phosphide and zinc sulphide(Salah 2019).Limitations on solar cell efficiency have been cited by researchers range from the loss of photons due to surface reflection to the loss of energy at the interface between the contact and silicon. Improving the metallurgical properties of silicon-based compounds reduces some of these losses.

Silicon is one of the most abundant elements in the earth's crust.For a solar cell to be produced,silicon compounds must be doped (intentional addition of chemical elements such as boron) to produce a semiconductor. The combining of differently contaminated semiconductor layers produces a p-n junction that is active in producing electrical energy when struck by light(Salah 2019).

Though metallurgical research is ongoing to find cheaper silicon based solar cells, there are three main silicon based solar cells; monocrystalline silicon cells, polycrystalline silicon cells and amorphous silicon cells. Due to the efficiencies displayed by these solar cells, their application is based on the economies of scale. Amorphous silicon solar cells are discussed by various researchers and authors such as Saga (2010) to be having low efficiencies (efficiencies less than 10%) and can only be used for very small-scale projects such as powering calculators. Thus for large scale-scaled municipal projects of powering for example municipal building lights, cost consideration must be critically evaluated to ensure that projects earmarked using amorphous silicon solar cells are cost effective. Saga (2010) indicates that metallurgical production is one of the three processes for developing a solar PV module. The other two processes are purification of silicon by physical methods and the purification of the same by chemical methods.

When selecting the type of PV solar panel to use, Gabra et al. (2014) state that the variance of the temperature levels mustbe carefully considered as each solar module is characterised by the temperature effect on its efficiency and output power. The authors go on to state that, since only part of the incident solar spectrum gets converted to electricity and the rest of the incident solar radiation diffuses as heat in the solar panel, the performance of and the temperature of the PV module must be within specification as the temperature in a module is a function of the incident power density, electrical power output and the thermal properties of the semiconductor material (cells) used in the module. An increase in module temperature results in a corresponding decrease of module efficiency and output power. To address the effects of temperature, a type of material developed to coat the solar panel surface (called anti-reflection coating [ARC]) must be considered so that as much light energy as possible is absorbed with minimal temperature increase in the module.

According to Moffitt et al. (2019), ARCs are crucial to improving efficiency in photovoltaics systems yet their advancement has received minimal attention especially when it comes to cost and durability at the air/glass interface.Shanmugam et al. (2020) state that ARCs are typically designed to minimise the undesired effects of reflection when light strikes the silicon wafer, and that its function is characterised by the range of wavelengths it permits. Citing Dong et al. (2018), the authors state that polished silicon can reflect upto 35% of the needed light energy for photovoltaic action. Thus, the authors state, citing Leon et al. (2017), that to enhance the performance or output of photovoltaics on solar PV panels, effective ARCs and light-trapping means must be employed with great design consideration.Some of the types of ARCs that can be adhered to the surface of a glass or lens in the module include near-infrared (NIR), short-wave infrared (SWIR), medium-wave infrared (MWIR), long-wave infrared (LWIR), and wavelengths in the visible spectrum. For the effective selection of an ARC for the location of the current study (city of uMhlathuze), weather forecast and solar irradiance must be understood.

In regard to enhancing the effective performance of solar PV modules, the above is inadequate if the light converging material or concentrators such as lenses are incorrectly selected. That being said, since the paper is to aid government (municipal) buy-in on procuring affordable and effective PV technology, selection of affordable light focusing lenses or alternatives are of paramount importance. Maintaining a balance between cost and performance is dependent on the discretion (focus) of the designer and municipal budget, but the following views are provided to constrain the design

and selection of the type of lens to be used. Researchers have established that:

- A solar PV module acts as a diode in cloudy conditions (low irradiance intensity conditions).
- Solar PV panels that have not been fitted with a lens arecostly because they require vast tracts of land to compensate for their low efficiencies. That is, these solar PV panels are expensive from the land costs perspective.
- Fitting of lens to a solar PV panel improves the efficiency of the panel, although this is an expensive addition. Different lenses are known and described by various authors;Fresnel lenses are used for illustration purposes in this paper.

Wallhead et al. (2012) state that although Fresnel lenses are used to concentrate the maximum amount of incident sun irradiance to the PV panel, there are three principal sources that result in efficiency loss: absorption losses, reflection losses and "geometric losses". The authors describe these losses as follows:

- Reflection losses are as a result of light striking the boundary of materials with different refractive indexes. This type of loss is dependent on the choice of materials, angle of incident light, and the design of the lens (Wallhead et al. (2012).
- Absorption losses are a result of sun rays passing through the material thickness. Heat energy is the main culprit here and thus losses are dependent on the properties of solar PV module components selected such as the ARC, and the optical path length in the lens.
- Geometric losses are as a result of uneven refraction light rays due to the shape of the lens, causing some of the light rays not to strike the wafer. The varying thickness of the lens causes variation in the refractive index therefore light rays striking the edges of the lens are refracted differently to those striking the lens near the centre. According to the authors, rays passing through the edges of the lens suffer greater chromatic dispersion.

Shanmugam et al. (2020) state that, in order to reduce reflection losses and make light available for PV conversion, ARCs must be used, and there are two main ways of implementing ARCs, as follows:

- Depositing thin multiple layered films on the surface of the wafer (substrate) to reduce reflection occurring because of different materials, and
- Incorporating graded refractive index (GRIN) coatings, which maximise the transmission of light by reducing the film refractive index from the refractive index of air to that of the substrate.

An empirical study conducted Li et al. (2014) regarding optimising the energy output (efficiency) of a PV silicon based solar cell in respect to positioning a convergent Fresnel lens at different heights above the cells, revealed that the efficiency of solar cells is greatest when the lens is positioned at a height that is slightly less (approximately 80%) than the distance of the focal point. Further, the authors suggested that positioning of the Fresnel lens at a height equal to the distance to the focal point results in poor energy output (poor solar cell efficiency or performance), the reason being that light is converged to a small spot size on the solar cell.

When the above has been designed and customised properly for institutions such as the uMhlathuze municipality, and with the rapidly falling price of solar PV panels, the implementation of large-scale solar power systems are more possible (Primo, 2016).Shanmugan et al. (2020) recommend further research into managing light in the solar PV system

using light trapping principles so as to optimise performance. Thus, if solar PV panels are adequately designed to optimise their efficiency for a specific location, the benefits of implementing solar PV technology at the City of uMhlathuzeare realisable, since other components such as inverters and energy storage are standard. In agreement with the above view, Nhleko and Inambao (2021) suggest that some components must be improved in accordance with the latest research, such as using supercapacitors than standard energy storages (capacitors).

2.2. Review of Institutional Attitude towards Piloting Solar PV Systems

South Africa is a politically driven country and a call has gone out from the national government for private-public partnership in resolving the energy crises of the country. Mughal et al. (2018) state that the political purpose of incentive policies in facilitating the initial small-scale deployment of the technology is to allow and support municipalities such as uMhlathuze municipality to pilot a solar PV system that is used to power lights or buildings, as a research and development (R&D) initiative to learn from. This attitude, according to Mughal et al. (2018), will provide a platform for the municipality to grow and achieve the economies of scale needed to reach grid parity.

Although views and discussions above indicatethat designers and municipal institutions must seek to select affordable highly efficient material for the development of an effective solar PV panel and system, technical personnel such as engineers, technicians and municipal appointed professional services providers within the municipality’s electricity planning section should also be obligated to seek for progressive solutions that will allow for small scale or cheap alternative materials to use to tackle energy disruptions and shortages.

Mughal et al. (2018) state thatthe converting efficiencies of monocrystalline silicon PV panels is in the region of 15%, polycrystalline silicon 12%, amorphous silicon 6%, and other thin film PV panels such as copper indium diselenide (CIS) and cadmium telluride (CdTe) 10 % to 13% and 8 % to 9% respectively.The technical personnel in the electrical department of the municipality must be allowed to procure,for instance, the easier to obtain and cheaper to procure amorphous silicon material and construct PV panels to subsidise energy supply.

Numerous media publications instigate a shared perception from citizens, private industries and municipal government institutions that electricity challenges in South Africa are Eskom’s alone,based on assumptions that the energy shortages are as a result of negligence in forecasting energy demands and poor maintenance of their infrastructure, however, the truth of the matter is that everyone has contributed to these shortages. The unfortunate reality is that there is an absence of a national government programme on energy audits at household level,on municipal facility and on industrial/commercial institutions that seek to measure energy wastage and enforce legislated penalty based system to citizenry and cited institutions. It is evident from Eskom’s three pastannual financial reports of 2017/2018, 2018/2019 and 2019/2020financial years, and uMhlathuze municipality’s past annual financial reports of 2018/2019 and 2019/2020, thatthe attitudes of municipalities towards creating innovative solutions in resolving the energy challenges of the country is lacking. Eskom has established various comprehensiveinstitutional-based and community programmes and strategies in an attempt to ramp up the energy status (capacity and stability) of power plants, energy usage awareness,reserve energy, and etc.

In view of the above mentioned, and also knowing that Eskom is not in control of consumer behaviour in how electricity is used, how then are category B municipalities with billions of rand budgetsin their electricity departments such as uMhlathuze municipality and metropolitan municipalities not held accountable in having initiatives and reporting on

those initiatives towards decreasing electricity demands from the national grid? This question stems from the ongoingcall that there should be public-private partnerships in resolving the energy challenges of the country. Worse, there is in place an adopted government policy that allows government institutions to appoint other organs of state and government established agencies such as the Council for Scientific and Industrial Research (CSIR), South African National Energy Development Institute (SANEDI), municipal infrastructure support agent (MISA), etc to assist government entities such as municipalities. Is there a gap in the integration of national and municipal targets and strategies, or is this the perpetuation of ill-considered views that national government challenges such as Eskom are their problems are not inclusive of municipal contribution?

Elaborating on the above views, Liff (2011) states that challenges faced by managers in government institutions such as municipalities aredue to the lack of support from their superiors and government budget cycle. Further, the author states that managers are not allowed or encouraged to devise innovative ways of solving problems, instead they are met with red-tape in trying to get approval for R&D initiatives. Thus managers in municipalities take paths of least resistance.

The Auditor-General's report in 2020 (Makwetu, 2020)reflecting on financial management in local government, had the followingfindings,among others:

- Billions of rands in funds that had been allocated to municipalities are managed "in ways that are contrary to the prescripts and recognised accounting disciplines", quoting unauthorised expenditure, irregular expenditure and fruitless and wasteful expenditure. A total of R32.06 billion rands was reported.
- Municipalities are dependent on grants and assistance from the national government, but fail to spend allocated funds due to red-tape in procurement activities, thus the inability to deliver affordable goods and services expected by citizens.
- There is little to no change in the way municipalities in the KwaZulu-Natal province function as accountability is inadequately practised and enforced by leadership, and the ongoing failure of key controls to financial management and funding of innovative solutions that better delivery of goods and services to communities.
- Increase in the procurement of professional services providers (consultants) and payment for services that have not yielded the desired deliverables.
- Increase in the appointment of professional services providers and yet there are personnel in the municipality's payroll (employment) employed to do what the consultants are doing.

Thus, the Auditor-General concludes, local government has sufficient monies and assets to fulfil the basic needs and aspirations of its citizens, however proper administration and supervisionover the financial affairs of municipalities is seriously lacking with devastating consequences.

3. RECOMMENDATIONS

In order for the South African government to conquer the energy challenges of the country, despite gathering innovative ideas of technically solving electricity problems, the following must be examined and corrective measures taken.

- Investigate the existing gaps that hinder the proper integration of municipalities with national calls and strategies, especially in solving challenges that affect every citizenry, such as electricity and water issues.

- Investigate the causes and red-tape that make personnel in the electricity planning departments of municipalities have negative attitudes or make no effort regarding R&D initiatives and projects.
- Investigate what lies behind municipalities having negative perceptions regarding their contribution to solving national challenges and yet they are government organisations equipped with personnel and resources to assist. If municipalities have some reliance on national government coffers, then shouldn't the national government sphere also expect technical support and initiatives?
- Qualify any essential commodity such as water, energy, and etc facing national crises to the national government crises programme that seek to enforce punishable measures to citizenry to resolve energy usage behaviours. This recommendation builds on the concept that Eskom runs an ongoing energy demand awarenessprogramme (EDAP) that reflects how power stations are pressurised by demand and what appliances must citizens' turn-off to alleviate demand. According to this paper, despite Eskom's effort of improved maintenance plans and programmes and increased fund allocations, the EDAP has not yielded the substantial desired results as load-shedding is still thriving, reflecting no significant change in energy usage trends and behaviour at households and industrial/commercial institutions level. Thus municipalities must be tasked to take stock of energy usage in their jurisdiction.

4. CONCLUSIONS

It seems obvious that municipal attitudes are to always receive support and financial assistance from government agencies, provincial and national government spheres. However, local government institutions can contribute to resolving national challenges by implementing small-scale innovative projects within their affordable means through empowering their managers and staff and also by allocating funds for R&D purposes. Thus, capable municipalities such as uMhlathuze and other metropolitan government institutions are encouraged to build their own location specific solar PV panels. Gabra et al. (2014) state that each location must be build's an affordable specific PV panel as each location weather conditionsare a function of temperature, solar irradiance and dust density. So, uMhlathuze municipality must be encouraged to incorporate solar technology to generate energy to power its respectivemunicipal facilities.

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